Analysis of the $Sn^{7+...14+}$ fine structure by optical and ultraviolet spectroscopy in an EBIT

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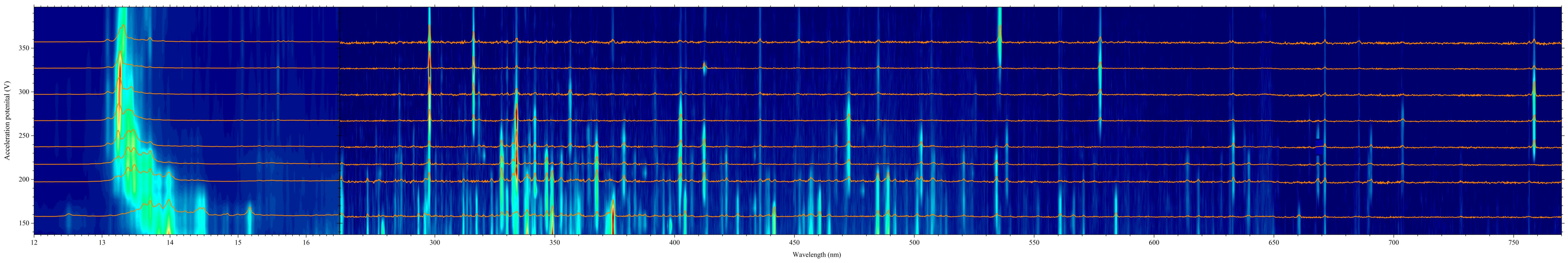
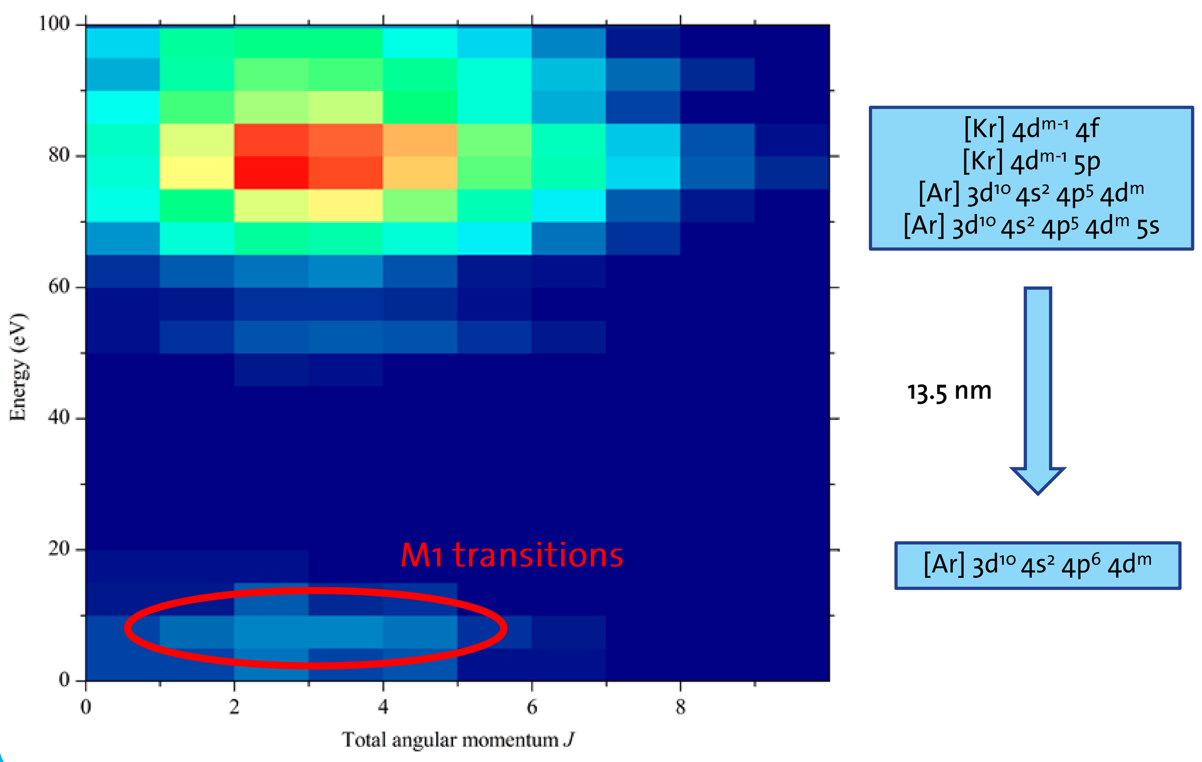
Highly charged ions of tin (Sn^{7+} - Sn^{14+}) are of technological interest as these are used in laser-produced-plasma (LPP) sources for the generation of extreme ultraviolet (EUV) light for nanolithographic applications. Here, we present the results from spectroscopic measurements of these ions, both in the EUV and optical regimes, obtained in a charge-state-resolved manner with the FLASH-EBIT (Electron Beam Ion Trap) at the Max Planck Institute for Nuclear Physics in Heidelberg. Transitions were identified by the use of *ab initio* Fock space coupled cluster calculations, thus confirming the predictive power of this tool. Our identifications were further corroborated using semi-empirical calculations within the Cowan code framework. With our experimental and theoretical work we have re-evaluated the fine structure of $Sn^{11+-14+}$, and comparison with previous, foundation-laying, studies suggest that some of their level identifications of the Sn HCIs atomic structure based on EUV spectral data need to be revisited [1].

Charge-state-resolved spectra



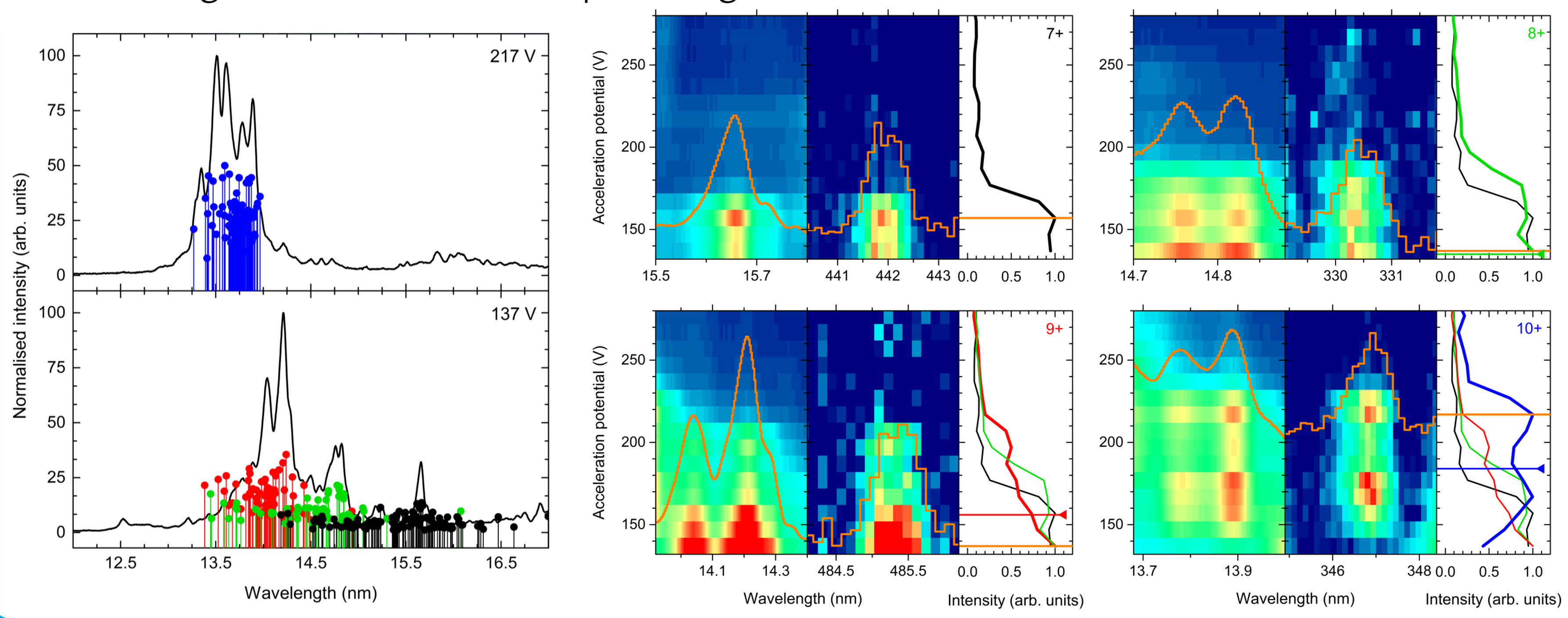
The atomic structure of Sn ions



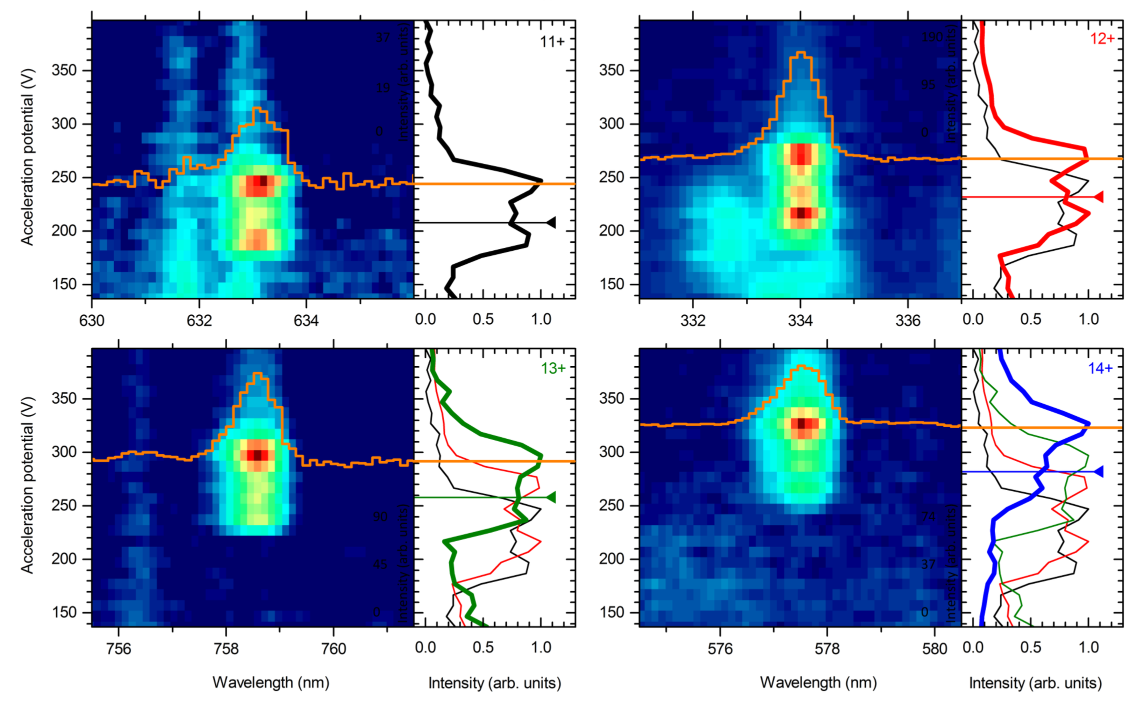
State density diagram $Sn^{7+...14+}$ ions contribute strong electric dipole transitions to an unresolved transition array (UTA). In the optical regime M1 transitions can be observed, directly connecting the ground state structure of these ions. In this regime, only few tens of transitions are present which can be resolved with ease, compared to the EUV regime.

Charge state identification (Sn^{7+} - Sn^{10+})

The EBIT EUV spectra are compared with known lines [2] to identify the emissions by the lower charge states of Sn in the optical regime.

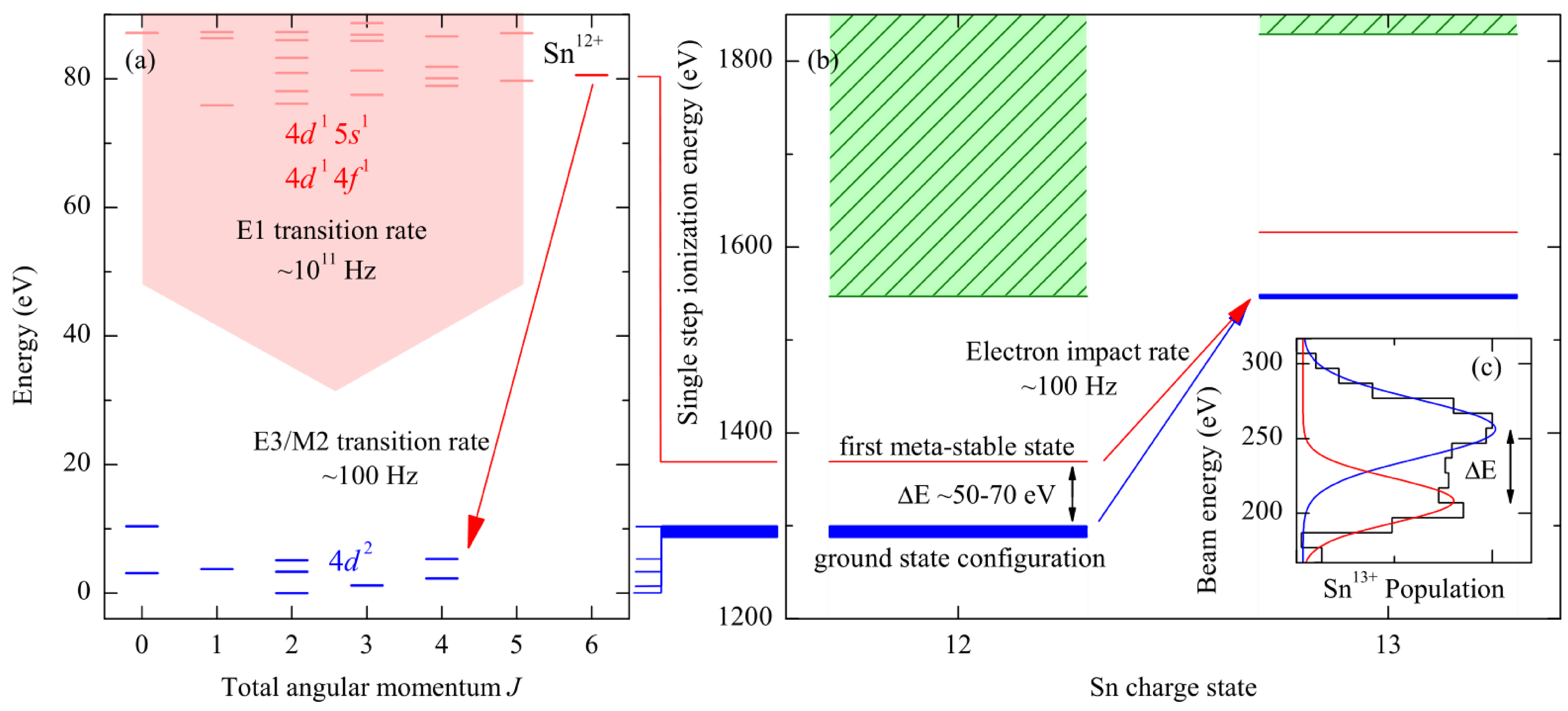


Charge state identification (Sn^{11+} - Sn^{14+})



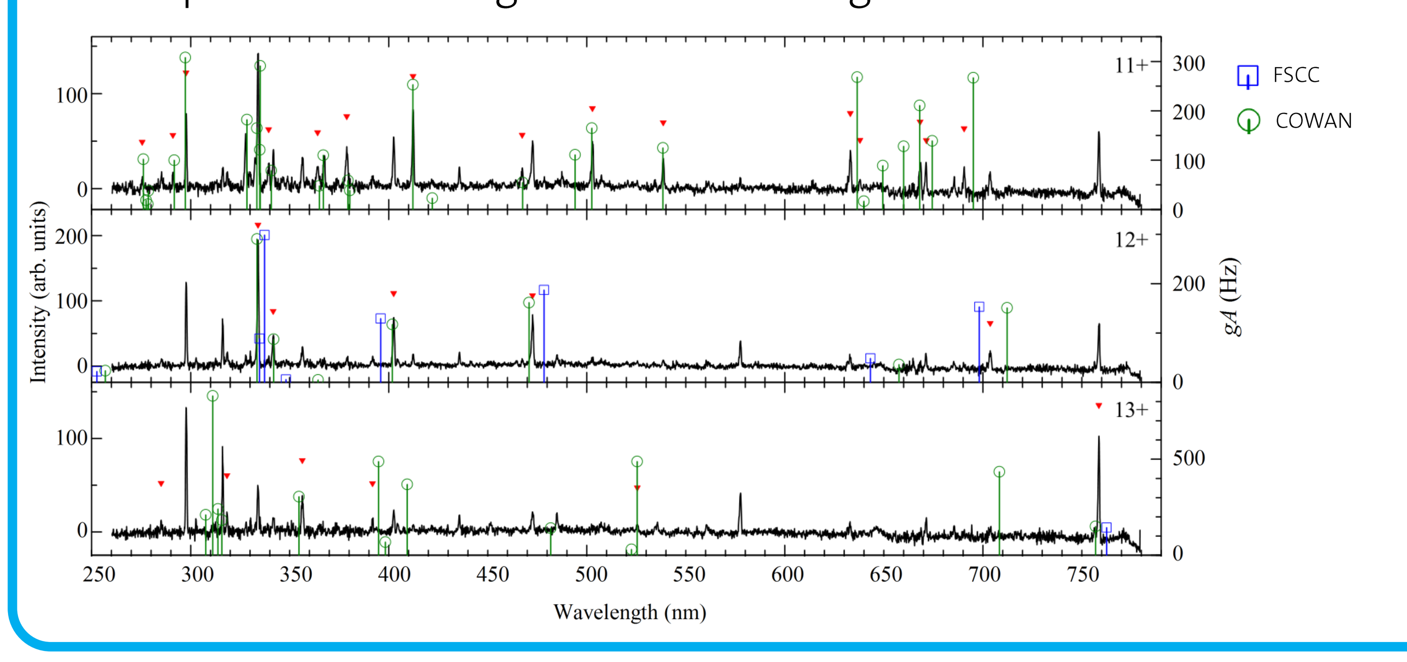
Fluorescence curves are used to assign lines to their respective charge states. The double-peaked structure of these curves and the fact that the florescence starts before the ionization potentials are strong evidence of metastable states populations inside the EBIT.

Fluorescence curves and metastable states



Comparison with theoretical calculations

Identifying optical transitions with the help of theory: Fock space coupled cluster [4,5] and semi-empirical calculations within the COWAN code framework [6]. This data enables a reinterpretation of the ground state configurations in the studied ions.



11+ Level	ΔE (cm^{-1})
$^4F_{7/2}$	-25
$^4F_{9/2}$	-28
$^2G_{7/2}$	-49
$^2H_{9/2}$	211
$^2H_{11/2}$	524
$^2D_{5/2}$	34
$^2G_{9/2}$	95
$^2F_{7/2}$	2005

Reinterpretation of 11+ levels

Conclusions

- 120 M1 transitions have been identified in the Sn ions of relevance for EUV sources;
- Our experimental input indicates the need for re-interpretation of foundation-laying work on the atomic structure of Sn ions (in Sn^{11+} - Sn^{14+});
- The majority of energy levels in the ground configurations of Sn^{8+} and Sn^{9+} have been determined;
- The predictive power of FSCC has been shown by the agreement with the experimental data.

References

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